

The FIR/Radio correlation of high redshift galaxies in the region of the HDF-N

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Abstract.

The correlation between the far-infrared (FIR) and radio emission is well established for nearby star forming galaxies. Many applications, in particular the radio-to-submm spectral index redshift indicator, tacitly assume that the relation holds well beyond our local neighbourhood, to systems located at cosmological distances. In order to test this assumption I have constructed a sample of 22 HDF-N galaxies, all with measured spectroscopic redshifts, and all detected by *both* ISO and the WSRT at 15 micron and 1.4 GHz respectively. The galaxies span a wide range of redshift with a median value of $z \sim 0.7$. The ISO 15 micron data were k-corrected and extrapolated to the FIR (60 and 100 micron) by assuming a starburst (M82) spectral energy distribution (SED) for the entire sample. An initial analysis of the data suggests that the correlation between the FIR and the radio emission continues to apply at high redshift with no obvious indication that it fails to apply beyond $z \sim 1.3$. The sample is “contaminated” by at least 1 distant ($z = 4.4$), radio-loud AGN, VLA J123642+621331. This source has recently been detected by the first deep field VLBI observations of the HDF-N and is clearly identified as an “outlier” in the FIR/radio correlation. I briefly comment on the impact upgraded and next generation radio instruments (such as *e*-MERLIN and the Square Km Array) can have in studies of star formation in the early Universe.

1. Introduction

The correlation between the far-infrared (FIR) and radio emission is one of the tightest and most universal correlations known among the global properties of *local* star forming and starburst galaxies (see Helou & Bicay 1993, and references therein). Entirely unexpected, yet extending across five orders of magnitude in luminosity, the physical explanation for the tightness of the relation is that the non-thermal radio emission and the thermal FIR emission are both related to processes governed by massive star formation. Established via FIR and radio observations of *nearby* galaxies, the FIR/radio correlation forms the basis of several key applications. In particular, the technique of using the radio-to-submm spectral index as a redshift indicator (Carilli & Yun, 2000) and the use of unbiased radio observations to estimate the global star formation history of the Universe (Haarsma et al. 2000). These applications are beginning to completely

overhaul our ideas of star formation and galaxy formation in the early Universe. In particular, deep SCUBA sub-mm observations of the high redshift Universe (e.g. Hughes et al. 1998) are beginning to reveal a dominant population of dusty, optically faint (early type) galaxies that are inferred (via the radio-to-submm spectral index redshift indicator) to lie at cosmological distances ($z > 2$).

A basic, yet crucial assumption that underpins these developments is that the FIR/radio correlation is entirely independent of redshift. However, there are many reasons why the correlation might well fail at non-local redshifts. In the radio domain these include (Condon 1992, Lisenfeld, Volk & Xu 1996), the quenching of the radio emission due to inverse Compton (IC) losses via the CMB (scaling as $(1+z)^4$). In addition, the trend for higher redshift systems to be more luminous (a selection effect related to current sensitivity levels) may also lead to global changes in the properties of the detected sources (as compared to local, less luminous star forming galaxies that form the basis of the locally derived relation). An overall change in the SED of these systems might well be expected, and the differing time scales associated with the rise in the FIR and radio emission may be significant, particularly for vigorous starburst systems. Specific effects regarding the level of radio emission might occur via (i) evolving magnetic field strengths (Dunne et al. 2000), (ii) varying levels of free-free absorption (Rengarajan & Takeuchi 2001), (iii) further IC losses associated with the intense *local* radiation environment and (iv) the possibility of significant “contamination” of high redshift star forming systems with co-existing low-luminosity, “radio loud” AGN.

Until recently a study of the FIR/radio correlation at non-local redshifts has been difficult since it requires extremely deep and complementary observations in both the radio and far/mid-IR wavebands, together with spectroscopic redshifts of relatively faint sources. Like many other areas of astrophysics, the situation has recently been transformed by the wealth of publicly available data generated by deep multi-wavelength studies of the Hubble Deep Field (HDF). In this paper I investigate the nature of the FIR/radio correlation at moderate redshifts (up to $z \sim 1.3$) assuming throughout the currently “preferred” cosmological model ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70$ km/sec/Mpc).

2. The ISO 15 micron and WSRT 1.4 GHz HDF-N Sample

A sample of 22 mostly low and moderate redshift HDF-N sources was established from the following simple criteria: (i) they are detected by *both* the WSRT at 1.4 GHz (Garrett et al. 2000) and ISO at 15 micron (Aussel et al. 1999) and (ii) each source is independently identified with the same optical candidate with a measured redshift (e.g. Cohen et al. 2001). No attempt was made to remove AGN candidates from the sample.

One limitation of this study is that the deep ISO measurements were made in the mid-infrared and it was therefore necessary to extrapolate the 15 micron measurements to 60 and 100 micron. This was achieved by constructing a SED based on the starburst galaxy M82 (this source has been extensively studied at all wave-bands including those that form the basis of our SED - the radio, mm, sub-mm, far, mid and near infrared bands). A k-correction (dependent on source redshift and our assumed SED) was also applied to both the mid-infrared and

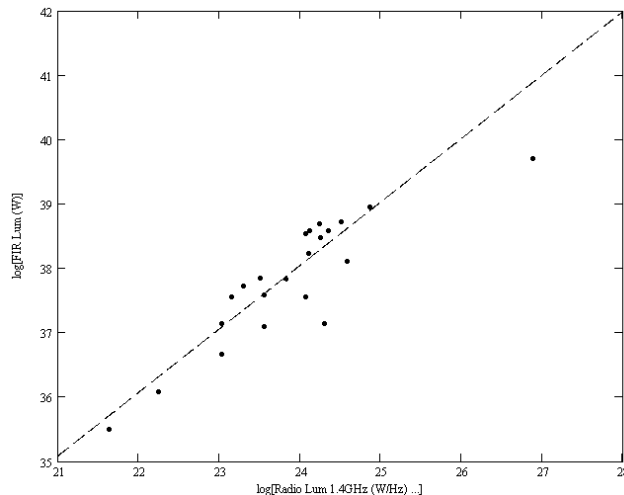


Figure 1. A logarithmic plot of the FIR vs Radio luminosity of the sample. A median fit to the data (solid line) is also presented - the FIR/radio correlation is clearly seen to apply out to $z \sim 1.3$. The distant ($z = 4.4$) radio-loud AGN shows up as an outlier at the far RHS of the plot.

radio data. Note that for non-local redshifts the steepness of the Rayleigh-Jeans tail in the FIR makes the k-correction absolutely essential, without this the *observed* FIR-Radio correlation completely disappears (it is this same property that, in principle, makes the sub-mm/radio spectral index such a powerful redshift estimator). I adopt the FIR/radio ratio as quantified in the “q” parameter defined by Condon (1992) viz: $q = \log\left(\frac{S_{100} + 2.6S_{60}}{3S_{1.4}}\right)$

3. Results

Figure 1 shows a logarithmic plot of the FIR and radio luminosities for the HDF-N sample. A median-fit to the data indicates the linearity of the relation (the slope of the fit is 0.99 with a correlation coefficient of 0.89). This striking result strongly suggests that the FIR/radio correlation continues to apply at non-local, moderate redshifts. Note that the luminosities probed by our faint (but distant) sample extends the range (upwards) by over an order of magnitude compared to previous, “local” studies. The highest luminosity sources in Figure 1 are also the most distant.

Figure 2 shows the value of q plotted as a function of redshift. There is a clear clustering of sources around $q \sim 2$ (excluding the radio-loud outliers). Given the dominant error involved in the process of extrapolating the mid-infrared fluxes to the far-infrared, this is similar to the value measured by Condon (1992) for local galaxies - $q \sim 2.3$.

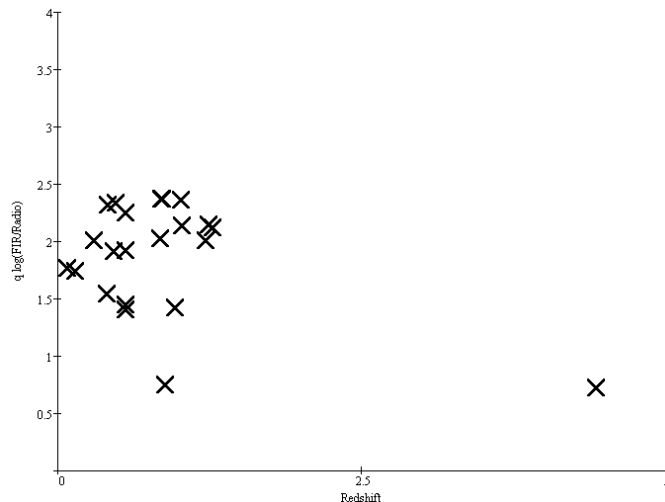


Figure 2. The ratio, q of the FIR/Radio emission plotted against redshift for each galaxy in the sample. Radio-loud AGN clearly show-up as outliers on the graph.

There are a few outliers observed in both Figure 1 and 2. One of these (the data point lying to the extreme right of Figure 2) is also (somewhat alarmingly) the highest redshift source in the sample. However, this $z = 4.4$ source (VLA J123642+621331) is widely believed to be an optically faint, dust obscured star forming galaxy, which also harbours an AGN (Waddington et al. 1999, Garrett et al. 2001, Brandt et al. 2001). The fact that it deviates from the FIR/radio correlation is in fact rather reassuring, and suggests that just as the locally derived correlation can distinguish between sources powered by AGN and star formation processes, the extended correlation can very likely do the same thing for moderate redshift sources. Figure 3 shows the European VLBI detections of three AGN in the HDF-N region (including our radio-loud AGN candidate, VLA J123642+621331). The EVN detection implies a small physical size for the radio emitting region and this, together with the radio source luminosity, strongly suggests that a radio loud AGN dominates the total radio luminosity of the source. Note that extremely deep, VLBI observations of the dust obscured, SCUBA source population, may be the best (only) way of currently disentangling the relative contribution made by AGN and star formation processes in these systems.

4. Conclusions

The FIR/radio correlation continues to delight - in addition to the puzzle of just why the correlation is so tight in the local Universe, it now appears we must also consider why it continues to apply to the more distant starburst galaxies presented here. There is no obvious evidence to suggest that the relation does

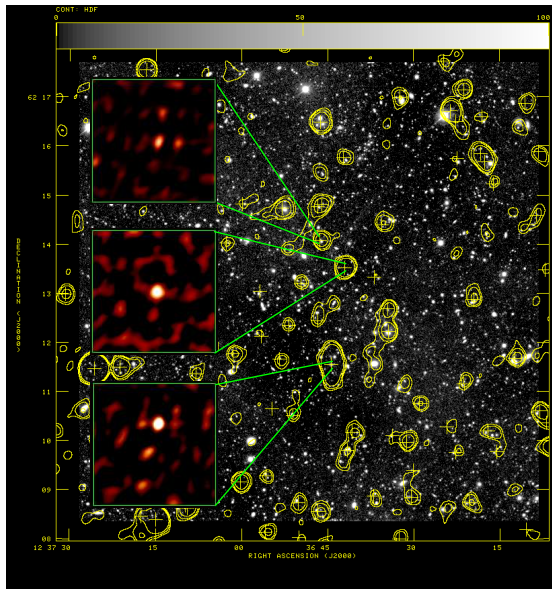


Figure 3. The three sources (including VLA J123642+621331 - middle insert) simultaneously detected by deep, wide-field EVN observations of the HDF-N.

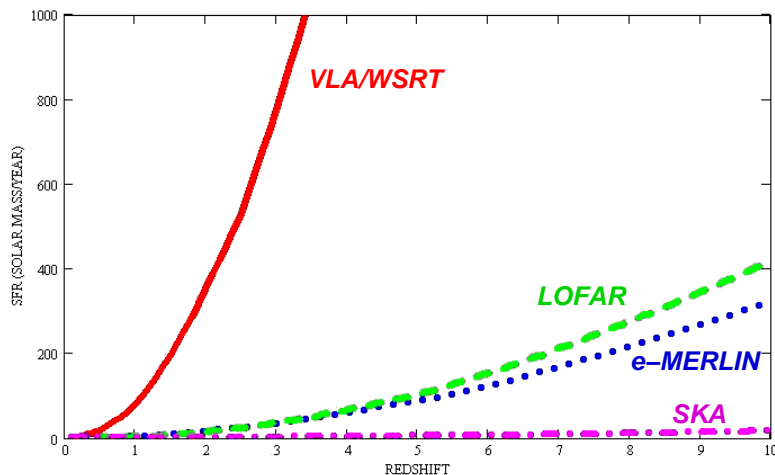


Figure 4. The (3 sigma) Star formation rates that can be probed by (i) deep field studies using current instruments e.g. 1.4 GHz WSRT & VLA - 48 hour integration (solid line), (ii) an 8-beam 120 MHz LOFAR - 1 month integration (dashed line), (iii) an upgraded 5 GHz *e*-MERLIN or EVLA - 96 hour integration (dotted line) and (iv) the 1.4 GHz Square Km Array - 12 hour integration (dot-dash line).

not apply equally well beyond $z \sim 1$. This is particularly happy news for techniques (such as the Carilli & Yun (2000) radio-to-submm spectral index redshift indicator) that implicitly assume this to be the case. The result also serves to re-emphasise the crucial role deep radio observations play as an unbiased estimator in studies of the star-formation history of the (largely dust obscured) early Universe. A more extensive investigation of the FIR/radio correlation at high redshift awaits much deeper SIRTf and ALMA infrared and sub-mm observations. Complimentary radio data will be essential and these depend critically on upgraded instruments such as those currently proposed (*e*-MERLIN and EVLA). However, truly next generation radio instruments, in particular the Square Km Array (SKA), will *completely* revolutionise our view of star formation in the Universe. SKA represents a quantum leap in our capability of detecting even relatively feeble/normal ($\sim \text{few } M_{\odot}/\text{yr}$) star forming galaxies out to any redshift that they might reasonably be expected to exist. Figure 4 shows the star formation rate than can be probed by current, upgraded and next generation radio instruments, assuming typical (but different) integration times.

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